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ROBOTIC FIREFIGHTING TECHNOLOGIES INTERIM REPORT

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14. ABSTRACT

This preliminary report focuses on the research and development (R&D) and demonstration of an unmanned ground system (UGS) technology suitable for tele-operated and autonomous robotic firefighting. The R&D effort was conducted by the Air Force Research Laboratory's (AFRL), Materials and Manufacturing Directorate (RXQ), Airbase Engineering Development Branch (RXQE). RXQE performed the demonstration at Ft. Drum, NY, a U.S. Army military reservation in support of AFRL's 2010 Tech Warrior Exercise. The demonstration involved the use of AFRL's developed unmanned firefighting vehicle (UFV), known as the "Fire Defender", to showcase first generation autonomous UFV behaviors to assist emergency first responders/firefighters in hazardous fire environments.

15. SUBJECT TERMS

First Responder, UGV, Ft Drum, Tech Warrior, Defender, unmanned firefighting vehicle (UFV), fuel fire, robotics, ATV, ultra high pressure (UHP), turret nozzle

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The Advanced Combat Firefighting Robotics (ACFR) demonstration was coordinated with the Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate, Airbase Technologies Division (RXQ), Airbase Engineering Development Branch (RXQE), the AFRL Tech Warrior staff, and the Ft. Drum Emergency Response personnel. The Ft. Drum Firefighting Training Test facility provided a good operational test environment with mock-up test beds including an aircraft, a JP-8 fuel pit, and a small compact vehicle. AFRL/RXQE would like to extend their thanks and gratitude to all of the following who contributed to the success of the demonstration and project:

- AFRL Tech Warrior Staff, specifically Colonel Ron Stauffer, Major Hank Jackson, Jason Clark and Philip Mumford, for inviting us to participate in the Tech Warrior exercise and assisting us with streamlining the coordination process of site selection, frequency approvals, logistical and safety planning.
- Ft. Drum Fire and Emergency Services Division Chief Bill Maciorowski and fire crew, with providing us access and use of their test facilities, emergency back-up support, and the presence of their personnel for operational feedback.
- ARA contractor engineering support, Kris Cozart, Charles Green and James Guske for the mechanical, electrical and software engineering designs of the unmanned firefighting vehicle (UFV) “Fire Defender,” respectively.
- Wintec contractor engineering support, Rommel Mandapat and Bordie Casiple, for the autonomous algorithm software development, and Bordie and Alex Evans for field test support.

1. SUMMARY

This preliminary report focuses on research and development (R&D) and demonstration of an unmanned ground system (UGS) technology suitable for teleoperated and autonomous robotic firefighting. The R&D effort was conducted by the Air Force Research Laboratory's (AFRL), Materials and Manufacturing Directorate, Airbase Technologies Division (RXQ), Airbase Engineering Development Branch (RXQE). Common field testing and demonstrations were conducted at Tyndall AFB, FL, in accordance with the Department of Defense (DoD) firefighting concept of operation (CONOPS). In addition, a demonstration was performed at Ft. Drum, NY, a U.S. Army military reservation, in support of AFRL's 2010 Tech Warrior Exercise. The demonstration involved the use of the AFRL-developed, unmanned, firefighting vehicle (UFV) known as the "Fire Defender" to showcase a first generation of autonomous UFV behaviors to assist emergency first responders/firefighters in hazardous fire environments.

AFRL/RXQE approached the project in three core phases. Phase 1 and 2 involved developing a teleoperated proof-of-concept UFV by implementing first a hand-controller-operated via line-of-sight (LOS) engineering model (phase 1), and then an operational control unit (OCU) using extended LOS to improve situational awareness (SA) and remote capability (phase 2).

While the first two phases concentrated solely on laying the groundwork by developing a standard teleoperated UFV system, the third phase focused on expanding the UFV's capabilities by integrating first-generation autonomous UFV behaviors. The embedded first-generation autonomous behaviors provided the UFV the capability to detect, track and extinguish a fire at the push of a button. RXQE investigated the implementation of stereovision by integrating a long-wave infrared (LWIR) sensor pair for feedback input to the autonomous control system.

Teleoperation capabilities are a common and mature UGS technology; however, integrating autonomous behaviors into a UGS is a difficult, task-dependent challenge. The key focus in this R&D effort was to develop a UFV with first-generation autonomous firefighting behaviors. RXQE was successful in demonstrating a teleoperable and semiautonomous UFV suitable for DoD firefighting CONOPS. Both Tyndall AFB and Ft. Drum provided relevant test environments to demonstrate the UFV's added remote firefighting capabilities in an aircraft fire scenario. However, to improve the art of autonomous UFV firefighting, additional sensor technologies and control methods need to be investigated to the overcome this challenge. For instance, wind in excess of 5 mph was a major problem that significantly affected the performance and accuracy of the autonomous UFV behaviors, as were blooming effects from saturated thermal reflections.

2. INTRODUCTION

2.1. AFRL/RXQE Team

Government Civilians (AFRL/RXQE): Lucas Martinez (Technical Lead)
Contractors: ARA—David Trevvett (Program Manager/Test Support), Wintec—Alex Evans (UFV operator support), Bordie Casiple (Test Support)

2.2. Purpose

The purpose of this project was to develop a UFV to demonstrate remote capability for fighting fires at safe distances via manual teleoperation and autonomously. Additionally, the first-generation autonomous features were developed for the UFV to detect and localize the position of the fire with respect to the platform, and autonomously apply fire extinguishing agent to the seat of the fire.

2.3. Background

Firefighters are faced with battling day-to-day common fires—dorms, base housing, etc., as well as the unique challenges of battling aircraft fires. Any of these types of fires place firefighters in hazardous environments, not just from the fire and heat, but from explosive materials such as aircraft bombs, and hazardous chemicals off-gassing such as carbon monoxide and "hydrogen cyanide (a byproduct of combustion of materials: insulation, carpets, clothing, and synthetics)"[1]. Consequently, fire environments pose extreme life-threatening risks to firefighters, which could result in the loss of human life.

Currently, U.S. military UGS systems are often used to provide protection against from Chemical, Biological, Radiological, Nuclear and high-yield Explosive (CBRNE) threats, and during Explosive Ordnance Disposal (EOD) and Improvised Explosive Device (IED) mitigation missions. For the past 3 years, AFRL/RXQE has been investigating ways to expand the capabilities of UGS to perform these missions by incorporating a teleoperated UFV.

Due to increased customer interest from the field and the inherent dangers involved in firefighting operations, Air Force Space Command (AFSPC) in conjunction with Air Force Civil Engineer Support Agency (AFCESA) requested the development of a proof-of-concept UFV. RXQE engineers from the fire research group with experience in extinguishing systems and robotics group with experience in developing UGS initiated a joint Fire/Robotics project. AFRL leveraged the project with the use of RXQE's base robotic vehicle platform, known as the Defender/Land Tamer®[2]. The initial R&D prototyping effort lasted only 10 months and ended with a successful demonstration at the Tyndall AFB, FL, fire pit in an aircraft fire scenario in late November 2008, shown in Figure 1.

The demonstration of the Fire Defender UFV proved it to be a safe, effective, and reliable means to defeat an aircraft fire—Fire Defender extinguished a JP-8 Class B fire within less than one and a half minutes, applying a mixture of 100 gallons of water and 3 gallons of 6% Aqueous Film Forming Foam (AFFF).

Figure 1. Fire Defender Demonstration at Tyndall AFB

2.4. Scope

This project comprised three phases during a 3-year effort. Phase 1 focused on the initial development of the UFV "proof of concept" by designing a firefighting payload and integrating it into AFRL's Defender unmanned ground vehicle (UGV) and simply teleoperating the UFV with a wireless hand controller via LOS. (Details of the system are given in Appendix A.) Phase 2 involved upgrading the UFV by developing an OCU to extend the LOS range, operator situational awareness, and controls. (Details of the upgrade are given in Appendix B.) Lastly, Phase 3 consisted of developing first-generation autonomous behaviors to control the turret nozzle to effectively apply fire extinguishing agent onto the seat of the fire.

2.5. Goals and Objectives

This project sought to advance the current state of technology available to DoD firefighters and emergency first responders by developing a UFV prototype able to extinguish small Class A, ordinary combustibles, fuel fires. AFRL's major goal was to deliver a working UFV prototype with manual teleoperation and autonomous control capabilities. To achieve this, AFRL/RXQE led the R&D effort and leveraged the existing teleoperated Defender UGV platform. Below is a list of the key goals and objectives of the project:

Goals

- Develop a basic teleoperated UGV with firefighting payload.
- Develop an OCU for the UFV.
- Develop first-generation autonomous UFV firefighting behaviors.
- Demonstrate and evaluate both manual teleoperated and autonomous UFV capabilities.

Objectives

- Demonstrate a proof-of-concept UFV to enhance DoD firefighters' mission capability.
- Extend the teleoperation LOS range and provide better situational awareness to the end user (firefighter).
- Expand the operational efficiency by automating firefighting methods.
- Demonstrate a UFV concept to the firefighting community to provide awareness of the current technology capabilities, to gain firefighter end-user acceptance, and to get operational feedback.

RXQE demonstrated and evaluated first-generation autonomous firefighting behaviors in a relevant testing environment during AFRL's 2010 Tech Warrior exercise at Ft. Drum's Firefighting Training Center. Tech Warrior provided the opportunity to test the robotic platform with the basic autonomous behaviors and robotic firefighting UFV technologies in the presence of fire fighters, potential future end users. In addition, the firefighters were able to provide the AFRL Robotics Team valuable feedback on the operator/user interface and controls, mobility, and firefighting performance. The collection of this input is beneficial to the future development of robotic firefighting platforms.

The implementation of a robotic firefighting vehicle is expected to significantly improve the safety and operational efficiency of emergency first responders by providing a safe stand-off distance from a remote position to mitigate such dangerous firefighting environments as space launch complexes, aircraft fires, and munitions and hypergolic fuel storage facilities, where a multitude of volatile fire hazards present a potential loss of life.

3. METHODS, ASSUMPTIONS AND PROCEDURES

With ever-evolving advances in the level of autonomy integrated into UGVs, RXQE confronted the tough challenge of developing first-generation autonomous firefighting behaviors to extend the capabilities and increase the efficiency of unmanned firefighting techniques, tactics and procedures (TTPs).

The R&D effort for phase III of the project began in 2010. The goal was to demonstrate that the Fire Defender UFV could accurately detect and determine the position and distance of the hot spot of a heat source (with respect to the UFV), autonomously direct the Fire Defender's turret to apply firefighting agent (water and foam mix) onto the hot spot and begin a sweeping pattern over the region of the heat/fuel source. This effort would be a first step into the world of unmanned firefighting autonomous behaviors, thus creating an innovative viewpoint from the traditional ways firefighters perform and execute their missions.

3.1. Methodology

In developing the first-generation UFV autonomous behaviors, computer stereovision technology was chosen as the primary sensor for the UFV. Computer stereovision is an advanced sensor used in robotics to create accurate depth perception and image localization of objects in three dimensional (3-D) space for obstacle detection and range finding. This technique is used to exploit the visual incongruity caused by the object's parallax when seen from one camera viewpoint versus another camera viewpoint.

Two cameras are used in stereovision applications to provide accurate visual perception and 3-D spatial detail. This is accomplished by a computer processing technique that compares the images, while shifting the two images so they are superimposed into one complete image. The amount the image is shifted is known as disparity. The disparity is then used to compute the distance to the object of interest.

For this application, the stereovision system comprised two Bullard® LWIR imagers to provide a centralized location of the heat source/fire. This unique configuration relays the distance and relative position data of the fire with respect to the UFV in real time. To correctly apply the firefighting agent onto the location of the seat (hotspot) of the fire, accurate feedback must be provided to command the turret's nozzle position.

To calculate the disparity of the object and the local position of the heat source the object of interest must be identified on both camera views. This task was simplified by the use of the Bullard® LWIR imagers, because these imagers have a mode that color codes the pixels in proportion to relative temperature. Using these data, together with baseline information and calibration data, it was possible to calculate the image disparity. The target depth is inversely proportional to the disparity measure and was used to fully define the local position of the heat source with respect to the cameras.

Figure 2 illustrates the theory of visual perception and shows how stereovision is interpreted by the computer's machine–visual interface. Camera views overlap in the green area and the computer merges the two views into one image. This region corresponding to the field of view of

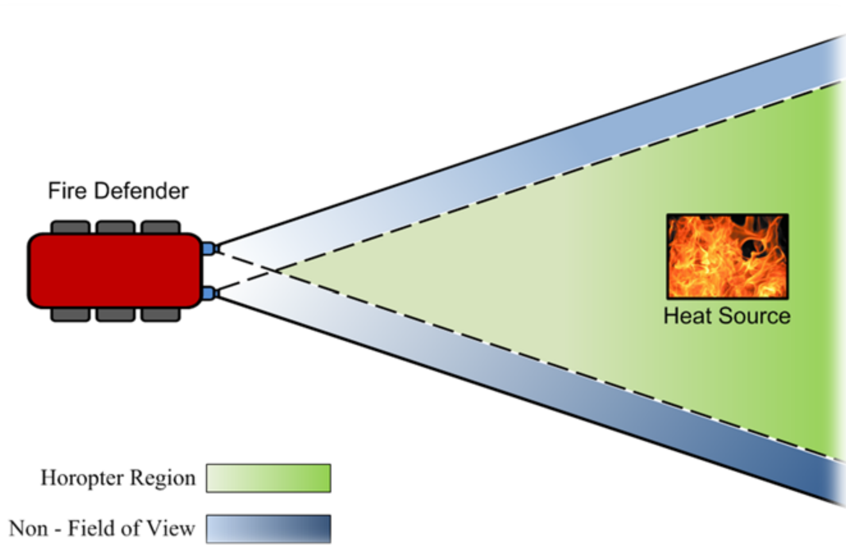

Figure 2. Depiction of Fire Defender Stereovision

the UFV's sensors is known as the *horopter*. The horopter contains all the visual information that provides the distance feedback from the heat source to the control system. Any objects of interest outside this field-of-view region cannot be identified with the implementation of stereovision.

The two bottom frames of Figure 3 are the left and right LWIR camera views, respectively, of the Fire Defender UFV. The blue region corresponds to the thermal region sensed by the LWIR. The images are digitally processed in near-real time to calculate the centralized 3-D relative location with the azimuth, elevation, and distance of the hotspot of the fire. The two top frames are electrical-optical (EO) camera views use to provide a visual perception of the front and turret view respectively, from the UFV during all modes of operation.

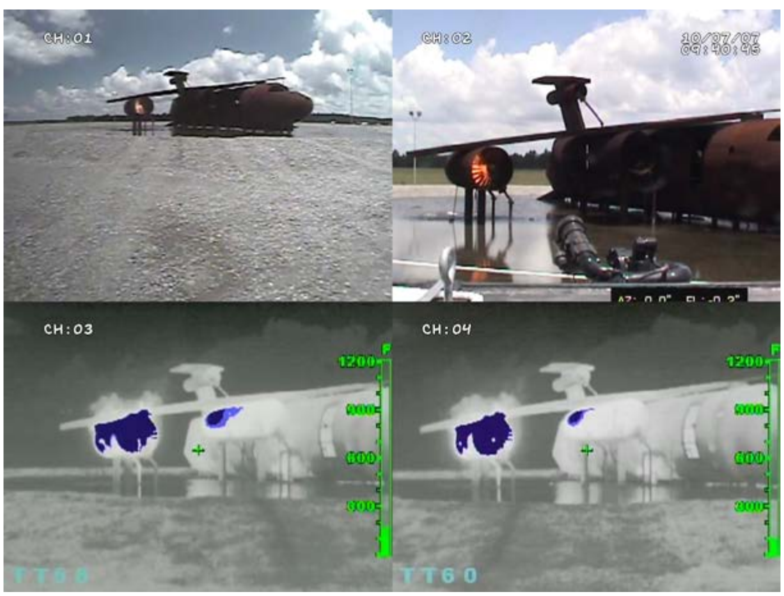

Figure 3. Visual and LWIR Left and Right Images

3.2. Technical Design Approach

To develop the first-generation autonomous control behaviors for the Fire Defender UFV, two LWIR cameras were mounted symmetrically about the center line of the vehicle with respect to the location of the turret to the existing UFV configuration. This creates the stereovision effect and provides enhanced visual LWIR data for the autonomous control system to acquire accurate hotspot distance feedback and control the turret's azimuth and pitch position.

3.2.1. System Design Modification

Figure 4 highlights some of the key essential components of the UFV system with the addition of the Bullard® LWIR cameras denoted by the number (4) label. These sensors provide the UFV with the stereovision data as control feedback to pinpoint the location of the hotspot of the fire. The electronically controlled turret (1) has a 180° pan/tilt control function to allow the turret full range of motion to direct the firefighting agent. With the digital infrared imager (2) and standard EO camera (3) the firefighter (end user) has the option to observe views from either the front or behind the turret on the OCU.

Figure 4. Fire Defender Autonomous Configuration

Figure 5 illustrates the modified version of the teleoperated Fire Defender controller configured with the enhanced autonomous mode and control features. This allows the firefighter to control the UFV in both teleoperation and autonomous modes. The left joystick (10) controls the mobility of the UFV, while the right joystick (7) controls the pan/tilt function of the turret. The controller is a plug and play device that connects into the OCU thru the universal serial bus (USB). In addition, the firefighter can switch through the various cameras views (9) such as the turret and front view. To engage in autonomous firefighting, the firefighter just switches to autonomous mode (1) and follows the sequence as instructed in Appendix C.

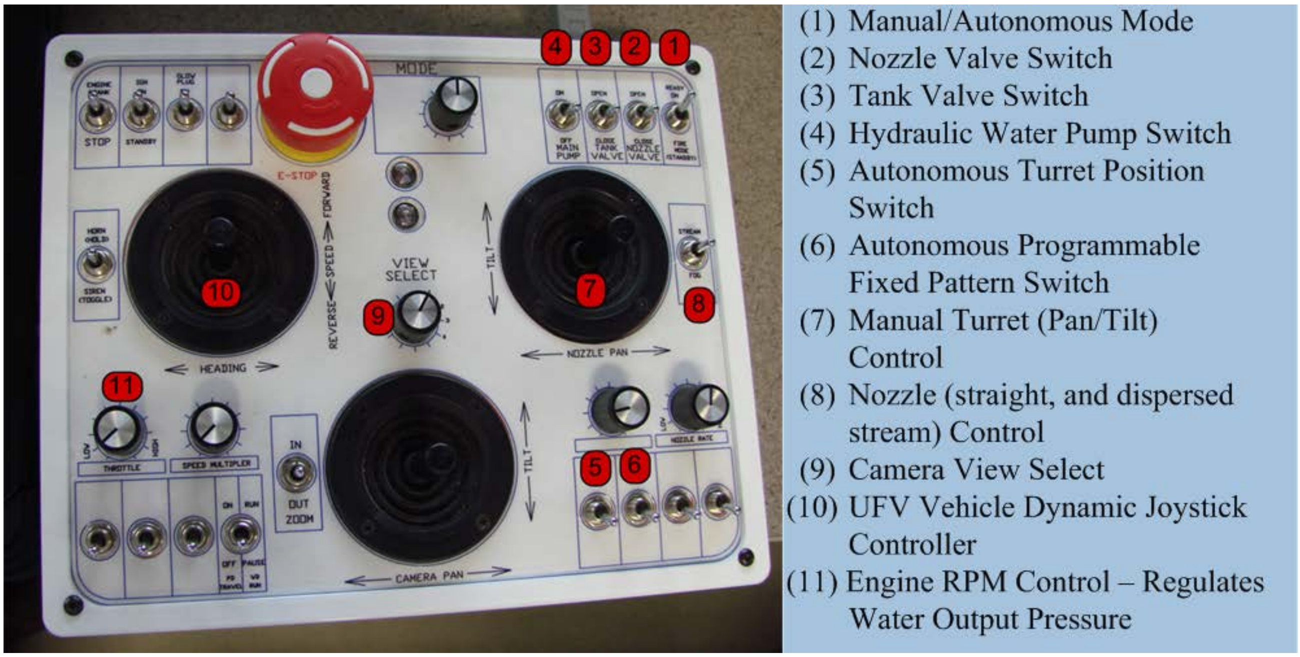

Figure 5. Fire Defender Controller

3.3. System Characterization

To achieve the challenging task of incorporating autonomous firefighting behaviors into the Fire Defender, two principal design objectives were investigated. The first and core objective was to find a thermal imaging sensor to identify and sufficiently localize the 3-D relative position of a hot spot region of a fire. This data feedback serves as valuable input to the control system to be able to direct the appropriate position (azimuth and pitch angle) of the turret.

The second objective was to acquire data to characterize the effective discharge distance of the firefighting turret nozzle with respect to its various pitch angles. The combination of both the distance feedback and turret performance parameters enabled the UFV's firefighting payload to be automated.

4. RESULTS AND DISCUSSION

4.1. IR Calibration

To evaluate the effectiveness of implementing a stereovision application with the LWIR Bullard® cameras and to provide the 3-D relative position of the seat of a fire, a test bed was set up consisting of a heat source (70 lbs of charcoal in a metal container) set at 50-ft intervals from 50 ft to 300 ft along the central axis of the Fire Defender. Data were recorded using the LWIR sensors at each incremental location for the computed distance of the hotspot region and compared to the actual distance.

Data revealed in Figure 6 illustrate that the computed distance from the hot spot became more accurate as the Fire Defender approached closer to the heat source. At 200 ft and closer the computed distance became increasingly more accurate and at the effective firefighting range of 50 ft the computed distance was within 5 ft tolerance of the actual distance.

The red and blue lines, respectively, in Figure 6 represent maximum and minimum distance computations by the stereovision software algorithm from five data sets at each 50-ft increment ranging from 50 ft to 300 ft.

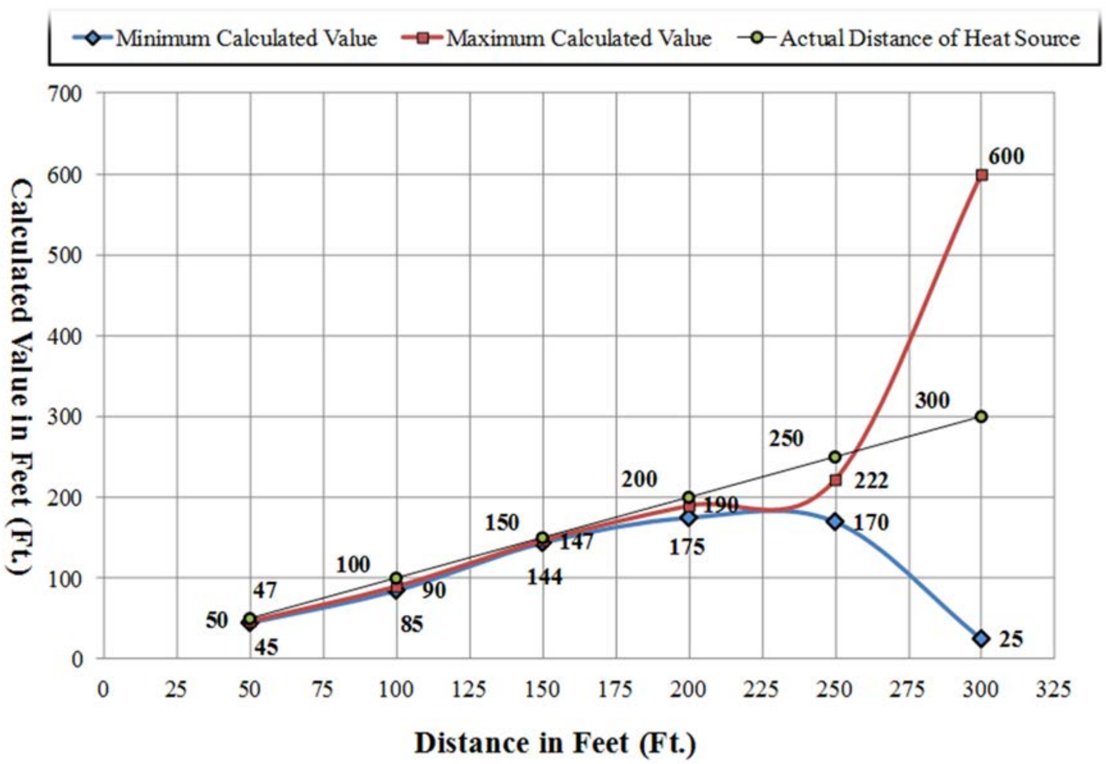

Figure 6. LWIR Stereovision Heat Source Distance Plot

The red cursor shown in Figure 7 identifies the centroid of the heat source to determine the distance, pitch and azimuth. At 300 ft the data were obscured due to the limitations of the LWIR

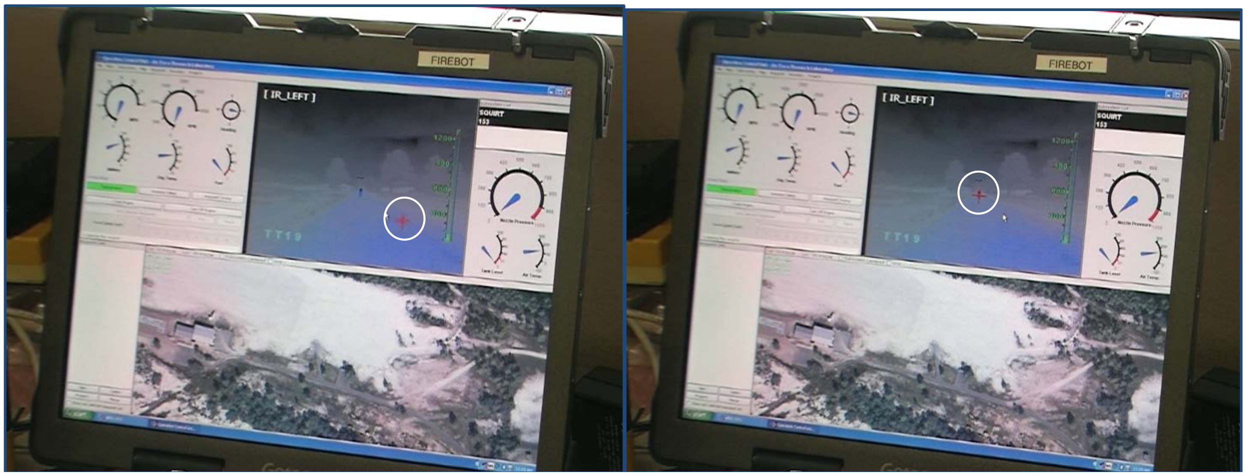

Figure 7. Left LWIR Camera Outputs at 300 ft

camera sensors. The gains of the sensors had to be adjusted to a high level to discriminate the heat source from heat reflecting from the pavement, which interfered with acquiring accurate thermal data. The real-time captured images of the left camera video feed in Figure 7 show the instability of the distance data feedback. The red cursor would vary back and forth consistently between the circled positions at around 300 ft, which corrupted the distance feedback data. Due to the erratic behavior of the red cursor at 300 ft, the stereovision software algorithm was unable to determine the distance accurately. However, as the distance neared 200 ft the accuracy of the computed distance improved significantly.

At 50 ft, the results improved dramatically and the red cursors consistently provided valid computed distance feedback with an accuracy of 5 ft. Figure 8 illustrates the stability and accuracy of the red cross-hairs pinpointing the hotspot region from both the left and the right LWIR camera.

Figure 8. Left and Right LWIR Camera Outputs at 50 ft

4.2. Modeling Effective Range of Agent Application

To characterize the UFV's effective range, the turret was set at different pitch angles beginning with the horizontal limit of 0°. The angle of pitch was adjusted incrementally around 5° to achieve approximately 10-ft increases in discharge range. It was found that the longest effective range of the firefighting system is 60 ft, but this varies depending on the direction of head, tail and cross winds.

Figure 9 contains collected data points characterizing the UFV's effective range. The second data point recorded in data set 2, where the pitch angle was zero and the trajectory remained at 50 ft, does not agree with the second data points recorded from data sets 1 and 3. This was a result of inconsistent behavior of the Fire Defender's vehicle hydraulic flow supplied to the firefighting system's hydraulic centrifugal pump. For all three cases, it was discovered that the stream breaks apart by the time it reaches 70 ft. The water stream is very sensitive to wind affecting both its range and lateral accuracy. These data points reflect ideal conditions, under which the wind is not a significant factor.

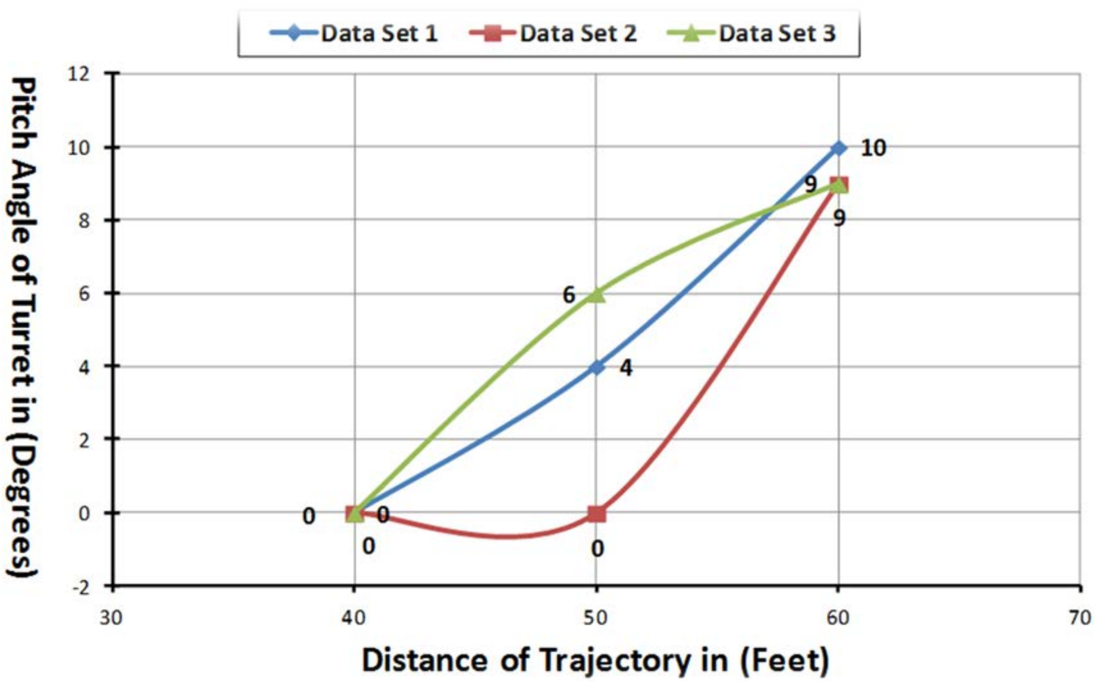

Figure 9. Turret/Nozzle Effective Discharge Range Plot

4.3. Field Evaluation of UFV Teleoperation and Autonomous Capabilities

In July 2010, RXQE personnel participated in AFRL's Tech Warrior exercise at Ft. Drum, NY. Tech Warrior served as a venue for AFRL scientists and engineers to conduct field evaluations in a relevant test environment with access to a mock-up aircraft, a jet fuel pit, and a vehicle-borne IED scenario. AFRL personnel provided a hands-on demonstration of the Fire Defender UFV to military and civilian firefighters (the end users), and interfaced with them to acquire operational feedback of the UFV's performance.

4.3.1. Tech Warrior Exercise Day 1

The RXQE team arrived at the Ft. Drum Fire Training Center to configure equipment and prepare for test experiments. In preparation the following was performed:

- Operational testing validated that the communication system, OCU, UFV and firefighting payload were functioning properly.
- Class A ordinary combustible fuels were used to ignite test fires that produced an 800 °F heat source. These fires were used to calibrate the Bullard® LWIR cameras used for fire detection at measured distances out to 100 ft in 20-ft increments.
- Agent throw tests evaluated the effective discharge distance of the firefighting agent.

The test equipment was configured and operationally tested, and no performance or functionality problems were encountered. The team established test parameters and configured a test bed for the experiments. Preliminary IR camera calibration and effective throw distance testing of the firefighting agent was conducted in preparation for tests. The most effective throw distance was between 60 and 75 ft with a total reach distance at 100 ft. Between 65 and 100 ft the stream was not concentrated and dispersed greatly. The IR cameras were effective in determining the location of the heat source at a distance up to 100 ft with a tolerance of ± 5 ft.

4.3.2. Tech Warrior Exercise Day 2

A series of experiments was conducted on fire detection and autonomous extinguishment software and behaviors.

Tests 1–3:

- Using the test bed constructed on day one, the team established a Class A heat source (450–800 °F) utilizing an aircraft mock-up to simulate an aircraft incident (the fire was located in the overwing emergency exit). Infrared (IR) camera settings were reconfirmed and weather readings were recorded (winds out of the south-southeast at 6 mph, 74 °F)
- The UFV was positioned at a stand-off distance of approximately 200 yd from the simulated aircraft fire and teleoperated in incremental distances toward the aircraft fire until it was within effective firefighting range.
- The IR system recognized the heat source and positioned the turret in the direction of the fire. The system automatically compensated for distance (elevation in relationship to distance) and was placed into autonomous firefighting mode.
- Firefighting agent was discharged from a distance of 60 ft in a sweeping “Z” pattern to maximize likelihood of effective application.
- LWIR camera gains, effective firefighting range and autonomous behaviors were recorded via an on-board digital recorder and stand-alone video recorders. Adjustments to the system were made to optimize extinguishing agent effectiveness and tests were repeated to validate previous test findings and system recalibrations.

Tests 4–5:

- Constructed a new test bed using the same graduated scale as test 1. The heat source was moved into the open to simulate a fire under the aircraft wing.
- The cameras were recalibrated and throw distances confirmed prior to the first underwing (open area) fire.

- The team followed the same protocols as above and, as indicated in the test plan, two more tests were completed.
- During the series of ground tests a marked difference in the autonomous elevation compensation for distance (resulting in farther overall throw distance) was discovered. This was attributed to the nozzle adjustment, fire location and weather conditions (sporadic and prevailing winds). Further testing and data collection were both repeatable and reliable.

A total of five calibrated tests were conducted utilizing an ordinary Class A combustible heat source and an aircraft mock-up to simulate an aviation accident. The UFV performed without failure and met expectations for autonomous fire detection and extinguishing behaviors. When calibrated to a given set of fire behavior parameters, early flame recognition and fire extinguishing behaviors were replicated. When the dynamics of the experiment were changed, the system was recalibrated and repeatable results were obtained. Data were recorded to validate the changes.

Due to the successful experiments during day two, the number of required experiments was completed and it was decided that advanced, large-scale testing was needed to better evaluate the system. The on-site support contact, Assistant Chief William Maciorowski, was contacted and he volunteered the use of the Fort Drum Class B fire pit and enough JP-8 aviation fuel to conduct two medium-scale pool fires. He also made an automobile available for use as a prop to simulate an IED explosion and fire. The remainder of the day was spent making preparations for advanced testing with Ft. Drum firefighting personnel.

4.3.3. Tech Warrior Exercise Day 3

The third day at the Ft. Drum Fire Training Center was used to conduct a series of experiments with the support of the Ft. Drum Fire Department. The experiments consisted of two JP-8 aviation Class B fires to simulate an aircraft fire, and a Class A fire in a car mock-up simulating an IED explosion and fire. The Ft. Drum firefighters controlled the UFV via teleoperation with the first-generation autonomous capability for these experiments.

Test 5 End User's Hands-on Demonstration

The Ft. Drum Fire Department created two, sequential, medium-scale pool fires at their Class B fire pit with ~50 lbs of JP-8. During these two tests, a firefighter was used as a test subject to evaluate the user-friendliness of the controls and to provide end-user feedback about the whole system in use. As part of the exercise, the firefighter fully controlled the UFV and extinguished the JP-8 fuel fire via teleoperation after activating the autonomous firefighting mode.

Test 6 Vehicle-borne IED Mock up

The Ft. Drum Fire Department set a Class A fire inside a car mock-up to simulate a car bombing fire. During this test, the RXQE team extinguished the fire and collected more thermal and video data.

Summary

The Ft. Drum Fire Department provided two additional advanced tests using their training facility and crew. This support enabled the gathering of valuable data along with additional user

feedback. The firefighters reported that having a firefighting robotic asset would be of great use in real-world situations that include dangerous HazMat conditions. During conversations with firefighting personnel, many of them expressed great interest in using such an asset at the Ft. Drum Army Post, where active range fires containing unexploded ordnance (UXO) occur quite frequently and pose extreme risks during firefighting missions.

4.4. Key Observations and Takeaways

As with any R&D effort in the early phases of development there were design challenges, concept refinements and considerations that need to be addressed and evaluated before entering the next level of research and development. To date, some key takeaways and issues associated with current R&D work include appropriate vehicle selection, firefighting performance, capacity, payload size, selection of a thermal imager sensor, refinements to the autonomous behavior software algorithm, and understanding how the use of a UFV will fit into the CONOPS of today's robotic firefighting.

The current Fire Defender vehicle platform, the Land Tamer®, served as a cost-effective prototype system for a proof-of-concept demonstration to exhibit robotic firefighting applications and autonomous behaviors. This UFV system is solely a proof of concept, which would not be fielded in its current form due to limitations in payload capacity, terrain mobility and performance capabilities. The next R&D iteration envisioned is to transfer the technology with improvements in both autonomy and terrain capabilities by implementing a large-scale tracked vehicle and adding an ultrahigh-pressure firefighting payload with a higher-capacity water tank.

Thermal imaging sensing is a critical component of the autonomous control system. For this application, two LWIR imagers were used in a stereovision arrangement. The selected LWIR imagers were successful in providing adequate feedback, but there were many limitations of the sensors' configured settings and features. Different intensities of fire required manual adjustment of the sensors' gains, meaning a person would have to make those adjustments on board the UFV. This is not practical in an unmanned firefighting scenario during the remote operation of a UFV.

It was discovered that large heat sources saturated the sensors because of blooming effects and reflections. This rendered the autonomous control system's algorithms useless in localizing the position of the heat source/fire without manual adjustments. The future sensor must have the ability to self-calibrate and include a range of gains appropriate to compensate for unpredictable fire sizes and temperature gradients.

Wind plays a significant role in the performance of the UFV system. Depending on the strength and velocity of head, tail or crosswinds, the dispersal application of the firefighting agent is unpredictable and imprecise. The current agent trajectories of firefighting system were characterized under ideal weather conditions where wind did not affect the parameters. Thus, further research needs to address compensating for this problem when implementing the autonomous solution/behaviors during adverse weather/wind conditions.

5. CONCLUSIONS

Robotic firefighting is an innovative concept that may significantly benefit firefighters with enhanced capabilities, operational safety and efficiency. Unmanned firefighting systems do not exist in the theater and are not in the hands of everyday firefighters. The fire community lacks awareness of the advantages of the UFV system technologies and its force multiplying capability. With a better understanding of firefighting mission requirements and CONOPS, unmanned firefighting systems can be designed to meet those needs.

Further research efforts to improve upon the current state of the art should focus on improving firefighting automated tasks. From an operational standpoint, it would be more effective for the end user to teleoperate the UFV in autonomous firefighting mode, so control of the firefighting system is hands-free and the operator's only focus is on controlling the vehicle. A more suitable LWIR sensor that can self-calibrate to the thermal response to avoid sensor saturation effects and discriminate thermal reflections in sensor feedback is required. Self-adaptive control algorithms need to be enhanced to compensate for factors such as wind, to differentiate between the actual fire and thermal reflection, and to distinguish multiple fires—as in the case of two isolated fires close to one another. The algorithm should be able to autonomously identify and engage them as separate fires, perhaps dependent on a priority command issued by the firefighter (end user).

6. REFERENCES

[1] Rochford, Richard, "Hydrogen Cyanide: New Concerns for Firefighting and Medical Tactics," URL: http://www.fireengineering.com/articles/2009/06/hydrogen-cyanide-new-concerns-for-firefighting-and-medical-tactics.html, last modified June 09, 2009. Accessed October, 6, 2011.

[2] http://www.landtamer.com/product/1/95, Accessed November 8, 2011.

Appendix A: Fire Defender Initial Prototype

The Fire Defender (Fig. A-1) is a Land Tamer® UGV fitted with a modular, self-contained 200-gal firefighting system/payload. The teleoperated UFV is controlled through a 2.4-GHz RF link by a portable customized Miratron® controller, which requires that the end user must maintain line-of-sight (LOS) contact and a physical visual of the UFV during operations. This allows the end user to be located at a relatively safe distance with an effective operating range up to 100 m.

Figure A-1. Teleoperated Fire Defender First-generation UFV Prototype

The controller for the initial UFV prototype was custom designed for the application. The left half of the unit controls the vehicle and the right half controls the functions of the firefighting payload, as seen in Figure A-2. The controls are supposed to be intuitive, allowing the firefighter to pick up the controller and operate the UFV in real-life situations with rapid response and engagement. Also, the controller is specifically designed to strap to the firefighter's waist line; the ergonomic fit provides comfort to the operator during use of the Fire Defender UFV.

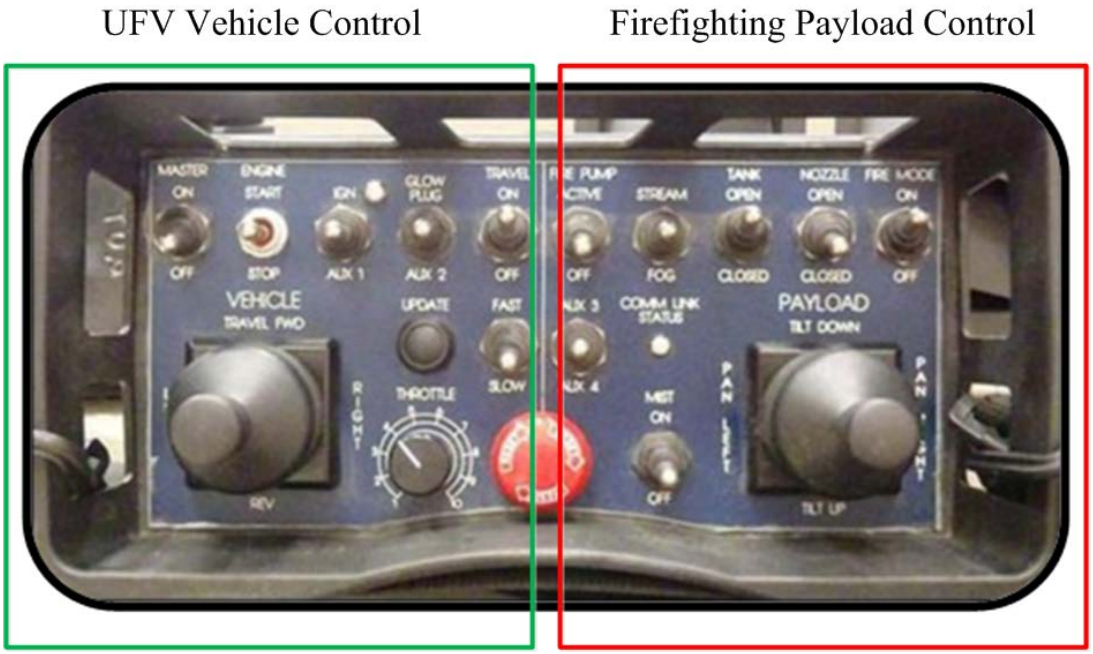

Figure A-2. Fire Defender Miratron Controller

Fire Defender Initial Prototype System Description
The first-generation prototype of the Fire Defender consists of the following platforms and specifications:

- Land Tamer® UGV Platform
  - 6 X 6 All-terrain Vehicle (ATV)
  - 60-hp Kubota® Turbo Diesel
  - Modular Payload Deck for Mission-Specific Applications
    - Force Protection
    - Intelligence, Surveillance & Reconnaissance (ISR)
    - Firefighting
  - 17-gal Fuel Capacity
  - 25–30 mph Max Speeds

- Firefighting Payload System
  - 200-gal Agent Tank
  - Hydraulically Powered Centrifugal Water Pump
    - 60 gpm @ 180 psi
    - 3 min of Firefighting Time
  - Ambient Temperature Sensor
  - Electronically Controlled Turret/Nozzle
    - Straight/Stream/Fog Adjustable Settings
  - User Intuitive/Friendly Miratron® Joystick Controller

Appendix B: Second-generation Fire Defender

As a result of the success of the initial R&D effort, in 2009 the AFRL Robotics Team expanded the Fire Defender's capabilities by extending the remote operating range to 2–3 mi LOS. The range was extended by incorporating a base station equipped with an OCU. Addition of the OCU allows the end user better situational awareness from onboard cameras displaying front, rear and turret optional views from the UFV, and it carries the additional advantage of separating the operator farther from the threat. Figure B-1 illustrates the enhanced controller and, on the OCU display, improvements to the UFV command and control scheme, vehicle data feedback (RPM, fuel level, etc.) and visual perception for the end user.

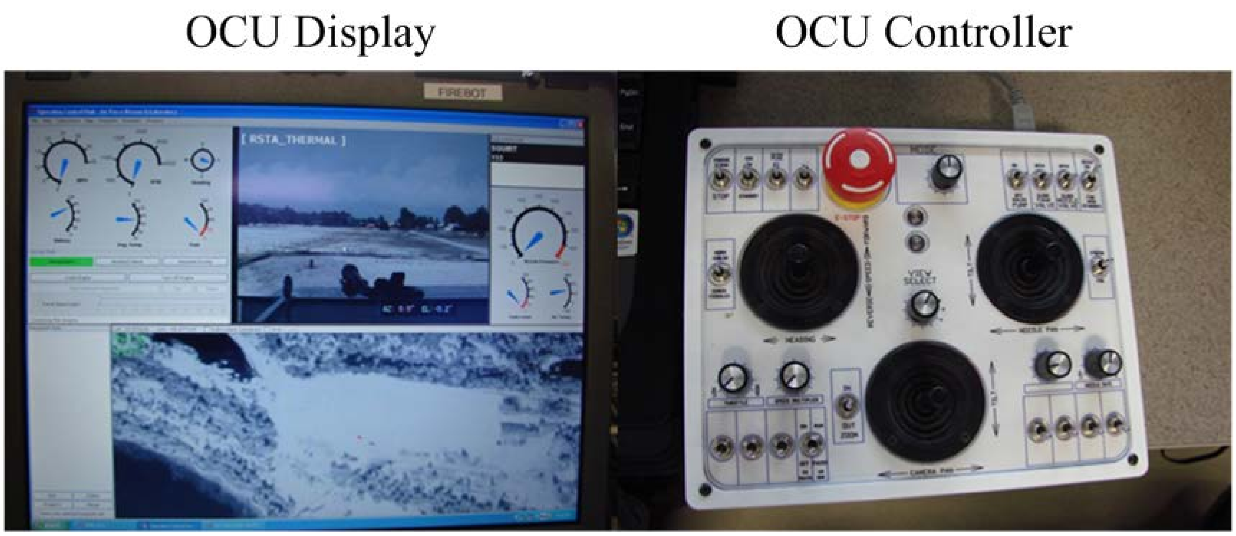

Figure B-1. Upgraded Fire Defender Operator Control Unit (OCU) Controller and Display

OCU Features

The OCU display consists of the following features:

- Vehicle Feedback (Located on the upper left corner of the OCU display)
    - Fuel, Engine RPM/Temperature, and Battery Levels
    - Heading (Compass)
    - Three Selectable Cameras (Views from the Front and Rear of the Vehicle, and from the Turret)
    - Geo-referenced Map Overlay
- Firefighting System Feedback (Located on the upper right corner of the OCU display)
    - Tank Level
    - Nozzle Pressure
    - Ambient Air Temperature

Appendix C: UFV Controller Procedure

The sequential steps and modes of operation to operate the UFV with the autonomous behaviors are as follows (referenced to Fig. C-1):

(1) Manual/Autonomous Mode
(2) Nozzle Valve Switch
(3) Tank Valve Switch
(4) Hydraulic Water Pump Switch
(5) Autonomous Turret Position Switch
(6) Autonomous Programmable Fixed Pattern Switch
(7) Manual Turret (Pan/Tilt) Control
(8) Nozzle (straight, and dispersed stream) Control
(9) Camera View Select
(10) UFV Vehicle Dynamic Joystick Controller
(11) Engine RPM Control – Regulates Water Output Pressure

Figure C-1. Fire Defender Controller

- To implement teleoperated control use the UFV vehicle joystick controller (10) to guide the Fire Defender to the effective range before engaging the autonomous firefighting system.
- Adjust the engine rpms with knob (11) for adequate water output pressure and flow for the firefighting system.
- Turn the Manual/Autonomous Switch (1) to autonomous mode
- Turn on the Nozzle (2) and Tank Valve (3) switches to enable water flow to the firefighting system
- Turn on the Autonomous Turret Position switch (5) to direct the firefighting Turret/Nozzle to slew to the central region of the fire.
- Turn on the Hydraulic Water Pump switch (4) to allow water to discharge from the firefighting system
- Turn on the Autonomous Programmable Fixed Pattern switch (6) to autonomously engage in the firefight. This feature controls the turret to cyclically repeat a figure eight pattern about the center of the hotspot region of the fire until disengaged. This pattern can be adjusted to various limits.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFRL	Air Force Research Laboratory
CONOPS	concept of operations
DoD	Department of Defense
EO	electro-optical (camera)
ft	feet
IED	improvised explosive device
IR	infrared
JP-8	jet propellant 8
lbs	pounds
LOS	line-of-site
LWIR	long wave infrared
mph	miles per hour
OCU	operation control unit
R&D	research and development
RXQ	Materials & Manufacturing Directorate, Airbase Technology Division
RXQE	Airbase Engineering Development Branch
3-D	three dimensional
UGS	unmanned ground system
UGV	unmanned ground vehicle
UFV	unmanned fire-fighting vehicle
yd	yards